Perioperative tidal volume and intra-operative open lung strategy in healthy lungs: where are we going?

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Abstract: Tidal volumes have tremendously decreased over the last decades from <15 ml kg(-1) to approximately 6 ml kg(-1) actual body weight. Guidelines, widely agreed and used, exist for patients with acute lung injury or acute respiratory distress syndrome (ARDS). However, it is questionable if data created in patients with acute lung injury or ARDS from ventilation on intensive care units can be transferred to healthy patients undergoing surgery. Consensus criteria regarding this topic are still missing because only a few randomised controlled trials have been performed to date, focussing on the use of the best intra-operative tidal volume. The same problem has been observed regarding the application of positive end-expiratory pressure (PEEP) and intra-operative lung recruitment. This article provides an overview of the current literature addressing the size of tidal volume, the use of PEEP and the application of the open-lung concept in patients without acute lung injury or ARDS. Pathophysiological aspects of mechanical ventilation are elucidated.

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Perioperative tidal volume and intraoperative open lung strategy in healthy lungs: where are we going?

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Abstract

Tidal volumes have tremendously decreased over the last decades from greater than 15 ml/kg to approximately 6 ml/kg actual body weight. Guidelines, widely agreed and used, exist for patients with acute lung injury or acute respiratory distress syndrome. However, it is questionable if data created in patients with acute lung injury or acute respiratory distress syndrome from ventilation on intensive care units can be transferred to healthy patients undergoing surgery. Consensus criteria regarding this topic are still missing because only few randomized controlled trials have been performed up to date, focusing on the use of best intraoperative tidal volume. The same problem has been observed regarding the application of positive end-expiratory pressure and intraoperative lung recruitment.

This article provides an overview of the current literature addressing the size of tidal volume, the use of positive end-expiratory pressure and the application of the openlung concept in patients without acute lung injury or acute respiratory distress syndrome. Pathophysiological aspects of mechanical ventilation will be elucidated.

Tidal volume in patients with ALI/ARDS

Early interest in low tidal volume (V_T) ventilation in acute lung injury (ALI)/acute respiratory distress syndrome (ARDS) was prompted by animal studies, showing that ventilation with higher V_T as well as high peak pressure result in pulmonary changes which mimic ALI. Ventilation-induced ALI is defined as injury with diffuse alveolar damage with pulmonary oedema, recruitment of inflammatory cells, and production of pro-inflammatory mediators (Fig. 1 and Fig. 2). Results from randomized controlled trials, evaluating the possible benefit of low V_T ventilation in patients with ARDS compared with traditional V_T ventilation, were divergent, showing a positive or no effect on mortality [1-4]. From 1996 to 1999, the National Heart, Lung, and Blood Institute ARDS Network enrolled 861 patients at 10 institutions in a randomized controlled trial, known as the Respiratory Management in Acute Lung Injury/ARDS (ARMA) trial [5]. Low versus high V_T and plateau pressure of < 30 cm H_2O were compared with liberal ventilation strategies. Hospital mortality rate was significantly reduced in the low V_T group compare to the control group (31% vs. 39.8%, $p = 0.007$). Additionally, these patients had a greater number of ventilator-free days (12 ± 11 vs. 10 ± 11 days, $p = 0.007$) as well as a greater number of days free of non-pulmonary organ failure (15 ± 11 vs. 12 ± 11 days, $p = 0.006$).

Tidal volumes in healthy lungs

With the knowledge of the benefit of low V_T ventilation for patients with ALI/ARDS, the crucial question arose if this ventilation strategy might also be applied to healthy patients. There are several reasons why this lung protective procedure should also be considered in healthy patients, even in the absence of clinical trial results. A first argument is the fact that patients under mechanical ventilation may develop lung injury during surgery. An example is surgery for empyema. These patients might suddenly experience a septic state with pulmonary involvement and would therefore - in the presence of ALI - benefit from a protective ventilation strategy. Secondly, patients with lung injury might not meet the criteria for ALI anymore, but would still benefit from a ventilation with lower V_T. A third group is represented by very ill patients, who are always at increased risk to develop ALI such as transfusion-related lung injury, ventilator-associated pneumonia, silent aspiration, etc. Although it seems likely that these patients would benefit from a lung protective procedure, there is currently no evidence available to support these assumptions.

Retrospective and observational studies

Numerous reports can be found about the topic of protective ventilation procedures for the lung, although the number is not as high as compared with studies focusing on patients suffering from ALI/ARDS. While most of these studies have been performed as prospective randomized controlled trials, several retrospective or observational studies on V_T exist [6-11]. Van der Werff retrospectively studied 197 patients and determined the incidence of postpneumonectomy pulmonary oedema [6]. The incidence of premanifest postpneumonectomey pulmonary oedema was 12.2% as opposed to an incidence of manifest oedema of 2.5%. Higher mechnical ventilation pressures during surgery were considered as significant risk factor (relative risk, 4.3; 95% confidence interval, 1.3 to 14.4 corrected for age and gender). Licker at al. performed a database study of patients operated of lung cancer between 1990 to 1997 in order to identify predictive risk factors of operative death [7]. A trend towards improved outcome was observed during the second period of the observation time, from 1994 to 1997, which could reflect a better understanding of the pathophysiological changes associated with thoracotomy under an improved ventilation strategy. Esteban et al. were the first to analyze a large number of patients, (n = 15'757), who had been prospectively enrolled in a multicenter international study on mechanical ventilation in intensive care units [8]. The analysis aimed at the identification of factors, influencing survival. The study showed that plateau pressures of more than 35 cm H_2O were associated with increased mortality. Similarly, Gajic and his colleagues retrospectively analyzed ventilated patients [10]. In this group of 3'261 patients they reported an odds ratio of 2.6 for V_T of more than 700 ml ($p < 0.001$) amongst other factors such as high peak airway pressure. Additionally, Gajic et al. reported about development of ALI/ARDS upon mechanical ventilation in patients with healthy lungs [9]. Within 5 days of mechanical ventilation, 24% of the patients developed ALI/ARDS. The main risk factors associated with the development of lung injury as assessed by a multivariate analysis were the use of large V_T, transfusion of blood products, acidosis, and a history of restrictive lung disease. Interestingly, female patients were ventilated with larger V_T (per predicted body weight) and tended to develop lung injury more frequently. Fernandez et al. collected intraoperative data regarding V_T in 170 patients undergoing pneumonectomy [11]. 18% of these patients experienced postoperative respiratory failure, and half of these patients even met criteria for ALI/ARDS. Risk factors for postoperative respiratory failure were intraoperative large V_T in addition to increased application of intraoperative fluids, the affected patients had been exposed to. All these retrospective and/or observational studies provide interesting insight with the caveat that they were not prospectively randomized trials.

Randomized controlled studies

Several studies were prospectively performed, testing the hypothesis that mechanical ventilation with large V_T and/or high inspiratory pressure could induce injury in healthy lungs and therefore could be deleterious. Most of these studies were performed during surgery with or without a short postoperative ventilation period on the intensive care unit. Therefore, the observational time was in general rather short. Additionally, levels of plasma or pulmonary inflammatory mediators were endpoints of these trials, no outcome markers were assessed. Lee et al. postoperatively included 103 patients on intensive care units and randomized them to a ventilation regime with a V_T of either 6 or 12 ml/kg actual body weight [12]. They found that the incidence of pulmonary infection tended to be lower with a smaller V_T, while the duration of intubation seemed to be shorter. Results of these trials were very promising. Wrigge et al. conducted a randomized controlled trial in 39 patients during elective surgery with 39 patients with anaesthesiologists physical status I-II [13] and measured plasma levels of various cytokines as indicators of inflammatory processes. V_T of 6 ml/kg with 10 cm H_2O positive end-expiratory pressure (PEEP) and zero PEEP (ZEEP) were tested versus 15 ml/kg with ZEEP. There was no significant difference in plasma levels of TNF-α, IL-1 receptor antagonist, IL-6, and IL-10 after one hour of mechanical ventilation. Similar results were found in 44 patients undergoing elective coronary artery bypass grafting surgery with 3 ventilatory strategies: 6 with 5 cm H_2O PEEP; 10 ml/kg V_T with 5 cm H_2O PEEP; 10 ml/kg with ZEEP [14]. No difference in plasma levels of TNF-α and IL-6 were detected. Wrigge et al. also performed a study including 64 patients with major thoracic (n = 34) and abdominal (n = 30) surgery [15]. V_T of 6, 12, and 15 ml/kg were chosen with 10 cm H_2O for the V_T of 6 ml/kg and no PEEP for the larger V_T. Determination of tracheal aspirate and plasma TNF-α, IL-1, IL-6, IL-8, IL-12 as well as IL-10 after 3 hours of ventilation showed again no intergroup differences. A first clinical trial with differences in TNF-α concentrations in bronchoalveolar lavage fluid (BALF) was detected in patients undergoing cardiopulmonary bypass surgery with V_T of 6 vs. 12 ml/kg predicted body weight for 6 hours [16]. Concentration of TNF-α was higher in the group of patients with larger V_T, while values of IL-6 and IL-8 did not differ between the groups. Zupancich et al. evaluated 40 patients with elective coronary artery bypass grafting surgery, comparing V_T of 10 - 12 ml/kg with 2 – 3 cm H_2O PEPP versus 8 ml/kg with 10 cm H_2O PEEP [17]. Larger V_T were correlated with an increase of BALF and plasma levels of IL-6 and IL-8. A clinical trial with the focus on coagulopathy was performed with of 6 ml/kg predicted body weight V_T with 10 cm H_2O PEEP and 12 ml/kg with ZEEP [18]. Ventilation with lower V_T prevented pulmonary coagulopathy as compared with ventilation with larger V_T, finding a less impressive increase in soluble thrombomodulin in BALF as well as lower levels of bronchoalveolar activated protein C after 5 hours of ventilation. Bronchoalveolar fibrinolytic activity did not differ by either ventilation strategy. A recent study was performed in 40 patients undergoing an elective surgical procedure, randomizing for 12 ml/kg V_T and ZEEP or 6 ml/kg and 10 cm H_2O PEEP [19]. Pulmonary myeloperoxidase release was increased in the patients managed with the higher V_T. BALF and plasma levels of TNF-α, IL-α, IL-1β, IL-6, macrophage inflammatory protein-1α and macrophage inflammatory protein-1β were not affected by the type of mechanical ventilation.

Rationale of using low tidal volume in healthy lungs

Many of the above mentioned clinical trials did not observe a statistical difference in the primary endpoints such as inflammatory mediators in BALF or plasma compared to controls. It is important to note regarding interpretation of the clinical trials, that the studies were not powered to draw clinically relevant conclusions on outcome measurements. They were performed with a relative small number of patients in different fields of surgery. The value of inflammatory mediators as surrogate markers of a clinical outcome is unproven. Additionally, a variety of cofactors such as positioning or the extent of surgical trauma were not assessed, which beside the V_T might be crucial for the development of pulmonary injury. In the past, ventilation strategies were recommended from various experts on this topic [20-23]. Based on the paucity of clinical trials, which have been performed up to date, the following recommendations can be made:

Practice points

- ***For a patient with a healthy lung, a tidal volume < 10 ml/kg predicted body weight should be used, while in a patient with an injured lung a tidal volume < 6 ml/kg is preferable.***
- ***A tidal volume < 10 ml/kg predicted body weight can be applied to patients without risk factors for the development of perioperative ALI/ARDS.***

PEEP and alveolar recruitment in patients with ALI/ARDS

PEEP is an essential component of mechanical ventilation. Several randomized trials have evaluated the efficacy of high levels of PEEP in the treatment of ARDS. Amato et al. compared a significantly higher PEEP in their intervention group compared with the control group (n = 53) (13.2 ± 0.4 vs. 9.3 ± 0.5 cm H_2O; $p < 0.01$) [1]. Also Villar and colleagues investigated in a similar trial (n = 103) higher PEEP values (14.1 ± 2.8 vs. 9.0 ± 2.7 cm H_2O; $p < 0.001$) [24]. Both studies showed a significantly lower ICU mortality rate in the patients with higher PEEP. In contrary to these data, Ranieri et al.

with a similar study design (n = 44) were not able to lower mortality rate with a high PEEP ventilation strategy [25]. The endpoints of this trial, however, aimed at levels of inflammatory mediators rather than at assessment of mortality. In order to determine a specific benefit of high PEEP ventilation in ALI/ARDS patients, a large randomized controlled trial (ALVEOLO - Assessment of Low tidal Volume and Elevated End-Expiratory Pressure to Obviate Lung Injury) was designed by Brower et al. (n = 549) [26]. Patients were randomized to ventilation with high or low PEEP (14.7 ± 3.5 cm H_2O vs. 8.9 ± 3.5 cm H_2O). Oxygenation was clearly increased in the intervention group with higher PEEP. However ICU mortality rate was similar in the two groups.

Gattinoni et al. showed that patients with early ARDS have multiple areas of atelectasis most commonly in the dependent lung regions [27]. This consequently leads to a reduced volume of the aerated lung. The importance of early lung recruitment and stabilization is a crucial aspect of ventilatory physiology. The 'open lung' - concept was first described by Lachmann in the injured lung with impaired surfactant system, requiring higher airway pressures to stabilize the alveoli [28]. The open lung represents a lung with little or no atelectasis and an optimal gas exchange. In the last few years, this concept has led to the open lung procedure, in which the lung is opened and kept open to minimize cyclic forces of alveolar opening and closing. The goal of this technique is to minimize cycle alveolar collapse and reopening. Recruitment is performed during 5 - 15 sec by pressure-controlled ventilation with a peak pressure of 40-60 cm H_2O and a ratio of duration of inspiration to expiration of 1:1 or 1:2. The peak inspiratory pressure is adjusted to the lowest pressure which keeps the lung open, ideally 15 - 30 cm H_2O with a PEEP of 10 - 20 cm H_2O to avoid alveolar collapse.

PEEP and alveolar recruitment in healthy lungs

What about patients with a healthy lung? Even if ventilation is performed in a healthy lung over a short time, this might represent a crucial factor for a potential development of ALI/ARDS. The open lung concept clearly aims at the injured lung, which is characterized by an impaired surfactant system with increased surface tension requiring higher airway pressures to stabilize the alveoli. However, atelectasis is also observed in healthy lungs during mechanical ventilation. Mead et al. demonstrated already in 1970, that in atelectatic areas shear forces act on the fragile alveolar membrane due to the pulmonary interdependence of the alveoli [29]. This leads to enormous shear forces between atelectatic and normal lung areas of up to 140 cm H_2O with transpulmonary pressures of 30 cm H_2O. These shear forces may be an important reason for epithelial disruption and the loss of the alveolar epithelium's barrier function. Epithelial disruption leads to high-permeability oedema with dilution of the surfactant and/or an inactivation of the surfactant by plasma components [30]. This surfactant impairment causes an aggravation of atelectasis. An important aspect hereby is the fact that formation of atelectasis already starts at induction of anaesthesia and consequently countermeasures should start early [31,32].

To avoid atelectasis, the strategy of 'open lung' might be useful even in non-injured lungs. No studies investigating open lung protective ventilation strategies regarding outcome have yet been performed during surgery. However, it was recently suggested that the open lung strategy may decrease pulmonary inflammatory processes, triggered by cardiopulmonary bypass [33]. Reis Miranda and colleagues performed a prospective single center randomized controlled study with 62 patients undergoing elective coronary artery bypass graft and/or valve surgery with cardiopulmonary bypass. Patients were randomly assigned to three groups with conventional mechanical ventilation, late or early open lung ventilation. Cardiopulmonary bypass caused a significant increase of IL-6, IL-8 and IL-10 in all groups. IL-8 decreased significantly more rapidly in both open lung concept groups, IL-10 only in the early open lung group, TNF-α, IFN-γ and IL-6, however, did not differ significantly between groups. Another focus in a study from Reis Miranda's group was the functional residual capacity after extubation [34]. The study showed that early application of the open lung concept resulted in a significantly higher functional residual capacity and fewer episodes of hypoxemia than with conventional mechanical ventilation.

What are the potential contraindications for an open lung strategy? Recruitment maneuvers with high inspiratory pressures have the potential risk for barotraumas. A recent study showed a correlation of high inspiratory pressures and elevated PEEP levels with an increased rate of pneumothorax [35,36]. However, both retrospective studies were performed in patients suffering from ARDS. Weg et al. found no significant correlation between high ventilatory pressures and the development of pneumothorax in a large prospective study with 725 ARDS patients [37]. Another concern of the open lung management might be the impairment of the circulatory system. Increased intrathoracic pressures are associated with a decrease in cardiac output [38]. Dyhr et al., however, reported that recruitment maneuver with two 20 sec inflations to 45 cm H_2O in combination with PEEP of 14 ± 3 cm H_2O can be performed safely in ventilated patients, even after coronary artery bypass surgery [39]. Cardiac index did not decrease after alveolar recruitment and application of PEEP. Similar results were found in other studies. Reis Miranda et al. investigated the effect of the open lung concept with recruitment maneuvers, followed by low V_T ventilation with elevated PEEP, on right ventricular outflow impedance during inspiration and expiration in 28 patients after cardiac surgery using transoesophageal echocardiography [40]. Right ventricular outflow impedance during expiration was not changed by open lung strategy, during inspiration right ventricular outflow impedance was decreased.

Rationale of using PEEP in healthy lungs

Prevention or attenuation of atelectasis formation should be performed by the following practice points:

Practice points:

- *PEEP should be used in selected patients (e.g patients undergoing general anaesthesia in lateral position, video laparoscopic surgery) at level not below 5 cm H_2O. Caution must be done in COPD patients as well as in patients whose expiratory flow does not reach baseline zero (Fig. 3).*
- *In selected patients as severe obese patients, PEEP should be used already at induction of anaesthesia.*
- *"Best" PEEP should be evaluated during anaesthesia according to clinical parameters such as plateau pressure, alveolar dead space or end tidal CO_2, arterial oxygenation and hemodynamics.*

Rationale of using open-lung maneuver in healthy lungs

The open lung concept of mechanical ventilation with recruitment and stabilization of the lung is according to the literature a useful ventilatory strategy in patients with ALI/ARDS. For patients with ventilatory support only during surgery, only a paucity of clinical trials exists, although the literature is growing. However, the number of elective surgery in patients with - in part - significant pulmonary co-morbidity is constantly increasing. Therefore, to avoid further damage (i.e. second hit), it seems plausible to apply open lung techniques even during elective surgery. This on the other hand has to be adapted individually as a variety of surgical factors (prone position, trendelenburg position, pneumo-peritoneum etc.) additionally influence ventilation physiology. Mechanical ventilation during video laparoscopic surgery and in morbid obese patients is widely treated in the dedicated chapter.

Practice points:

- *It is suggested that patients with impaired arterial oxygenation or affected by high chest wall impedance (e.g. morbid obese patients or patients with high abdominal pressure) might benefit from ventilation according to the open lung concept (recruitment manoeuvre over 5 - 10 sec under pressure-controlled ventilation with a peak pressure of about 40 cm H_2O, inspiration to expiration ratio 1:1, PEEP above 5 cm H_20 followed by adjustment of set pressures.*
- *Gentle recruitment technique is required.*

One-lung ventilation

Patients with ventilation for lung resection have an increased risk to develop ALI. ALI after lung resection is relatively infrequent, occurring in 2.5% of all lung resections combined, with a peak incidence of 7.9% after pneumonectomy. However, it is associated with a high morbidity and mortality rate of around 40% [41]. Causative factors of lung injury beside inflammatory processes induced by the surgical procedure are ventilatory trauma, transfusion, hypoxia-reoxgenation upon one-lung ventilation (OLV), etc. [42,43]. A prospective trial underlined the hypothesis that alveolar hypoxia, followed by reoxygenation and re-expansion, respectively, triggers the release of inflammatory mediators [44]. In a retrospective analysis of risk factors for ALI after lung resections increased duration of OLV represents a crucial risk factor for the development of ALI [43].

Ventilatortion strategy

As a consequence, the ventilatory management for patients undergoing thoracic surgery is very demanding. A special challenge thereby is the procedure of OLV regarding ventilatory considerations as well as the device, which should be used for lung isolation.

V_T: For many years, hypoxemia was considered as the most important problem during OLV. Therefore, guidelines were based on the results of clinical trials focusing on an improved oxygenation, independent of the V_T. Katz et al. showed in the early 80's, that large V_T produced the highest pO_2 values during OLV [45]. As a consequence common recommendations was the use of a V_T of 8 - 12 ml/kg for two- as well one-lung ventilation procedures. With increasing amount of study results, it became clear that a protective ventilatory strategy as mentioned before is also crucial in situations of OLV to prevent ALI. One of the most important and most widely cited animal studies came from Gama de Abreu, who investigated in detail V_T reduction for OLV in isolated rabbit lungs [46]. This group showed that OLV with high V_T and ZEEP is injurious in the isolated rabbit lung model. Wrigge and colleagues investigated cytokine levels in patients undergoing OLV [15]. However, with high or low V_T ventilatory strategies, no difference in pulmonary or systemic levels of measured inflammatory markers was found. Schilling et al. pointed out the increased production of pulmonary inflammatory mediators during OLV upon ventilation of the depended lung with V_T of 10 ml/kg compared to 5 ml/kg [47]. A study with 52 randomized patients undergoing esophagectomy from Michelet et al. with OLV with 9 ml/kg ZEEP versus 5 ml/kg PEEP 5 cm H_2O revealed evidence for a lower cytokine levels in the protective ventilation group [48]. Again, these studies did not focus on the outcome of the patients.

Fraction of inspired oxygen (FiO_2): Hypoxemia is a constant threat during OLV. Traditionally, 100% oxygen was used to prevent hypoxemia during OLV, to improve peripheral oxygenation, increase blood flow to the ventilated, non-deflated lung, decrease nausea as well as improve wound healing [49-51]. Despite the advantages application of 100% oxygen offers, it is correlated with certain risks for the patient. High FiO_2 can cause absorption atelectasis and therefore might indirectly trigger ALI. Additionally, hyperoxia may cause airway hyperresponsiveness - although only demonstrated in an animal model - and may promote the formation of radical oxygen species, which could jeopardize the lungs, inducing inflammatory responses [52,53]. Diseased lungs might be more susceptible to injury than healthy lungs [54].

PEEP: Application of PEEP for OLV faces some more aspects as for two-lung ventilation. The patient is in a lateral decubitus/decubital position with the dependent lung being compressed by additional gravitation, being implied with a potential for elevated airway pressure and atelectasis. Fujiwara et al. performed a study, examining patients undergoing OLV with different PEEP values [55]. The dependent lung was ventilated for 20 min with 10 ml/kg V_T with ZEEP in a stepwise fashion, followed by a ventilation with 4 cm H_2O PEEP. Application of PEEP significantly increased oxygenation and decreased the shunt fraction. Also Senturk et al. demonstrated that PEEP improved oxygenation during OLV [56]. Response to PEEP during OLV seems to be individual and therefore has to be evaluated during ventilation [57]. Slinger et al., titrating external PEEP according to the lung–chest compliance of each patient, found that with the application of 5 cm H_2O PEEP oxygenation improved in 14%, however, had no effect in 65%, and even decreased oxygenation in 21% of the patients. An important aspect seems to be the interaction between V_T and PEEP to minimize alveolar damage [58]. All these studies are very interesting, but beside Michelet et al. they did not define ALI as endpoint.

Alveolar recruitment: Lung recruitment during OLV seems to be efficient as shown in the study of Cinnella et al [59]. In this study, lung recruiting maneuvers improved oxygenation, although transient hemodynamic derangement occurred during the maneuver. Tusman et al. studied the effects of alveolar recruitment maneuvers in 12 patients undergoing thoracic surgery in the dependent lung during OLV [60]. Patients under this strategy showed improved oxygenation as well as increased ventilation efficiency. However, re-expansion of the lung may be harmful, as evaluated in an animal model [61].

Ventilation: Normally, a volume-controlled ventilation strategy (volume-controlled ventilation, VCV) is used in the operating room during surgery. For OLV, the question arises, if a pressure-controlled management (pressure-controlled ventilation, PCV) would be better, offering a more homogeneous distribution of ventilation and improving ventilation-perfusion mismatch. This research question was evaluated in 48 patients undergoing thoracotomy [62]. In the first group of patients (n = 24), OLV was initiated with VCV, followed by a switch to the other mode of PCV. Ventilation modes were performed in the opposite order in the second group (n = 24). Peak airway and plateau pressure were significantly higher in the VCV, oxygen tension smaller and intrapulmonary shunt more pronounced. Other studies have confirmed these findings of improved oxygenation, reporting significant lower peak and plateau pressure values when using PCV [56]. Despite the application of 4 cm H_2O PEEP in the study of Senturk et al., airway pressures in the PCV-PEEP mode were still lower compared with VCV with ZEEP. In a more recent study, however, no significant difference between VCV and PCV was found [63]. Fifty-eight patients undergoing thoracic surgery were ventilated as follows: in the VCP group, a V_T of 9 ml/kg with ZEEP was chosen to reach the same inspiratory airway pressure as in the PCV group. No significant difference in oxygenation was observed between both ventilation strategies, while peak airway pressures were higher during OLV with VCV. Based on the literature, no clear arguments exist for a PCV.

The following recommendations are based on several reviews [64-66]:

Practice points:

- *A reduction of the tidal volume to a maximum of 6 ml/kg predicted body weight and a limitation of the plateau airway pressure to less than 20 cm H_2O is recommended.*
- *Inspiratory oxygen concentration should be minimized as much as possible.*
- *The use of 5 - 10 cm H_2O PEEP should prevent atelectasis.*
- *Although the issue between volume vs pressure controlled ventilation is not yet clearly defined, PCV should be preferably used.*

- *Recruitment manoeuvre is recommended with caution according to the above mentioned settings by taking into account all the possible negative effects of heart-lung interactions.*
- *Gentle recruitment technique is required.*

Devices for lung isolation devices: Double-lumen endotracheal tubes (DLT) and bronchial blockers seem to be clinically equivalent regarding performance in providing lung collapse for patients with normal airways [67]. Each device offers its advantages depending on the patient and the type of surgery. Intubation maneuver with DLT is more demanding because of the larger size and the special shape of the tube. In patients requiring a rapid sequence induction, a DLT is more difficult to insert than a single-lumen tube, followed by induction of a bronchus blocker [68]. The use of a wire-guided endobronchial blocker via nasal offers also safe way for patients with restricted mouth opening for esophagectomy [69]. Comparing effectiveness of lung isolation, lung collapse was achieved within 17 min with a DLT, versus 19 - 26 min for the bronchial blocker [70].

Recommendations

Based on the recommendations of an article by Campos, absolute lung separation can be better achieved with a DLT, while the use of a bronchus blocker is recommended in situations with difficult airways [67]. Both devices are tools for only well-trained thoracic anaesthesiologists.

Research agenda

- ***Many clinical trials have been performed in patients with ALI/ARDS, elucidating application of low and high tidal volume and/or PEEP, and the use of the open lung concept. Only a paucity of studies is available in patients with healthy lungs. As a consequence an immense need emerges to design prospective randomized clinical trials.***
- ***Clinical trials are warranted regarding surrogate endpoints for ventilation strategies such morbidity and mortality.***
- ***Differential aspects of ventilatory procedures and their impact on outcome remain to be determined.***

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Figure legend

Fig. 1

Mechanism of ventilation-induced lung injury.

Fig. 2

Left side: Normal alveolus.

Right side: Alveolar overdistention induces endothelial and epithelial cell injury with alveolar formation of oedema.

Fig. 3

Flow diagram of a ventilated patient with suspected compromised exspiration (flow at the end of the expiration does not return to zero baseline).

Figure 1
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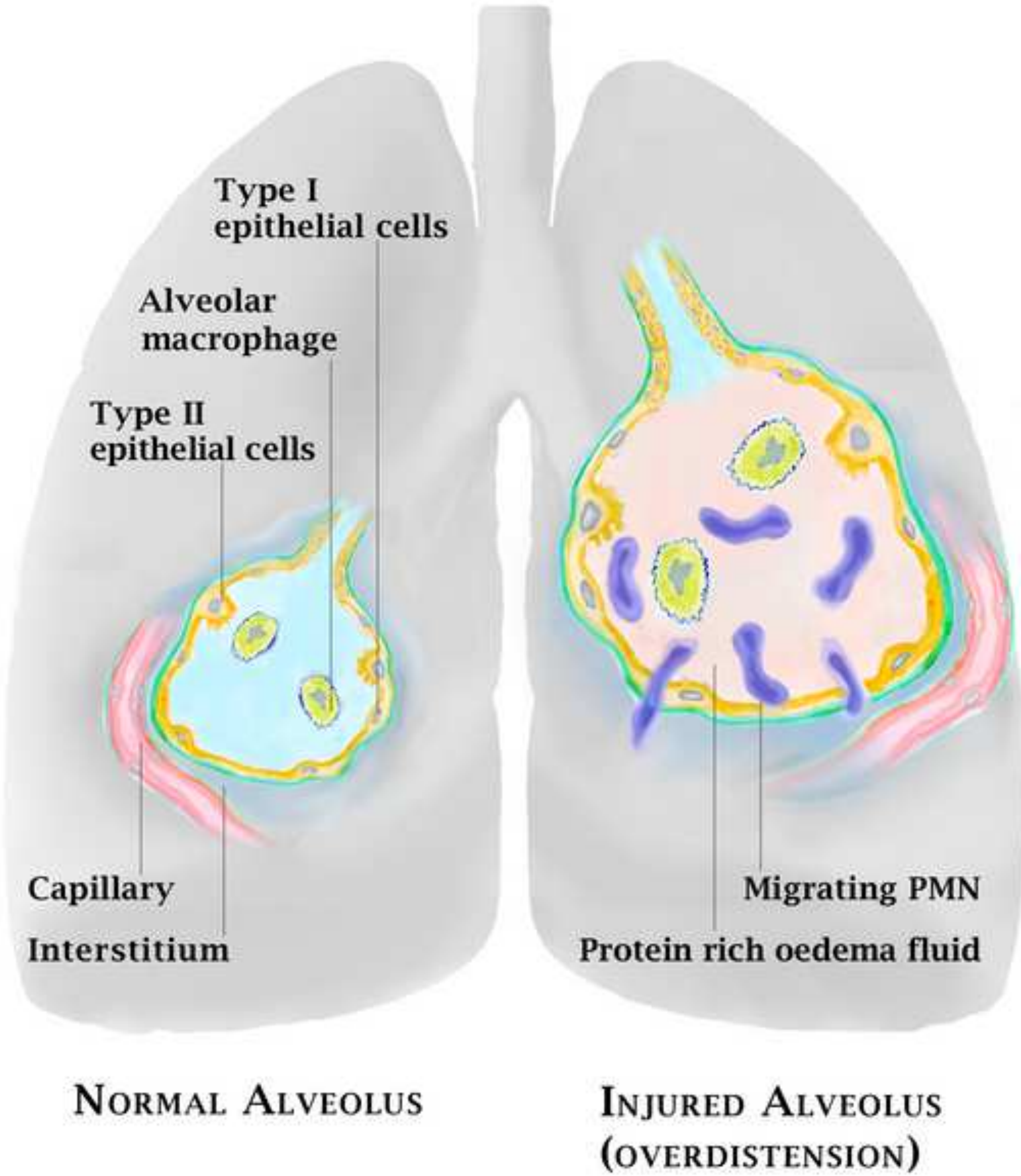

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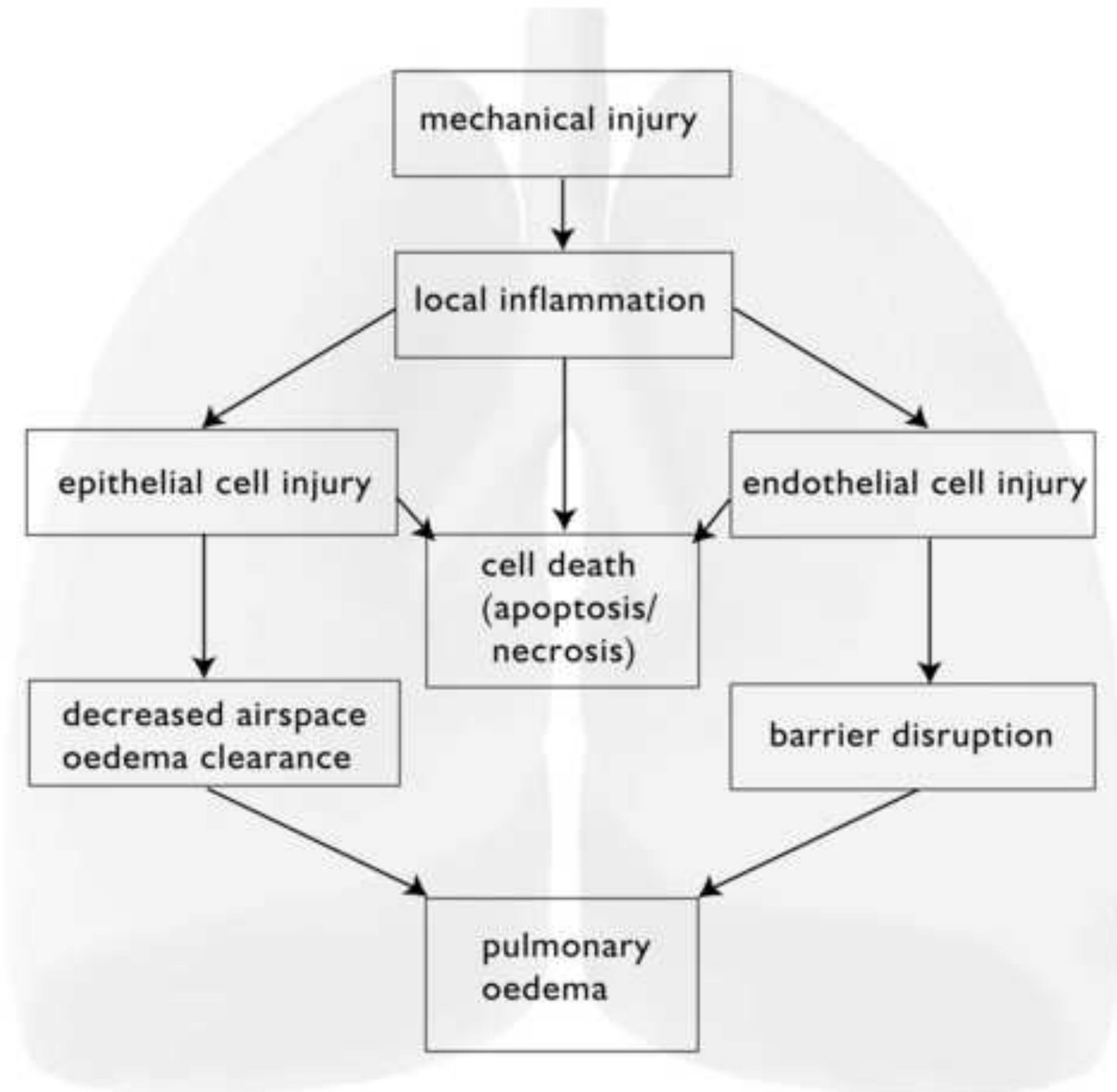

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